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Decision-support framework for the environmental assessment of water treatment systems

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A B S T R A C T

Environmental assessments require the development and analysis of a large amount of data. Decision-makers must manage considerable amounts of information just to obtain a viable set of alternatives. The environmental assessment proposed in this study is a decision-support framework that facilitates obtaining results that endorse the decision-making process.

This study aims to provide a fast and straightforward analysis of the influence of energy consumption in water treatment systems (energy-for-water) and its impact onto the environment, considering water quality requirements, water distribution systems, and how different energy combination setups affect these variables. The framework was applied to countries on the seashore experiencing water scarcity distress and world average greenhouse gas emissions regimes as examples, but it can also be applied to other types of systems.

Energy-for-water greenhouse gas emissions can be decreased through the awareness-related measures reflected in the selection of energy sources, changing water desalination process, optimizing water intake, choosing water reuse, and using untreated seawater in industrial processes. Countries with the highest greenhouse gas emissions continue obtaining electricity from coal. Likewise, greenhouse gas emissions are lower in countries using nuclear energy as a source of electricity. However, the reliance on nuclear energy often depends on stakeholder approval.

1. Introduction

Arid and semi-arid regions experience serious water supply deficiencies, and water infrastructure development is the primary challenge in these areas (Banihabib et al., 2017). In Chile, mining operations are located at high altitudes and in hyper-arid regions where the amount of mineral resources exceeds water demand for processing. Water availability and cost are critical factors for economic and environmental feasibility of new projects and for the expansion of existing mines (Oyarzún and Oyarzún, 2011). Seawater is currently used in mining operations without desalination (Cu, Co, Zn, Mn, Ni, Mo, Pb, Au, U, and iodine extraction), so the process must be adapted to new conditions involving possible interaction of dissolved elements with minerals, chemical agents, and equipment, also the relationship between desalinated water production and the use of fossil fuel causes economic, social, and environmental problems (Cisternas and Gálvez, 2018).

High energy consumption of water treatment processes is the reason why operational costs are significant. Improvements in energy efficiency have been the focus to reduce carbon footprint and greenhouse gas (GHG) emissions (Feliciano et al., 2014; Plappally and Lienhard, 2012). Energy is needed for construction, maintenance, treatment, monitoring, and pumping, which are the most energy demanding activities, including supply, use, and disposal of fresh water, wastewater, and recycled water (Plappally and Lienhard, 2012; Rothausen and Conway, 2011). Energy demand of water transfer systems is highly dependent on the density, topography, and the location of raw water extraction and wastewater release (Loubet et al., 2014; Rothausen and Conway, 2011).

Unsustainable use of fossil fuels can be reduced; some approaches include wastewater treatment and water reuse, reduction in water consumption (water efficient technologies, infrastructure

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and piping network improvements, and public awareness), and implementation of renewable energy (Mezher et al., 2011). The use of non-traditional water sources involves many implementation challenges including its energy-intensive requirements. Demand for energy in the water sector has increased because of the growing water demand, which has created the need for integrated water and energy management to identify energy saving opportunities (Rothausen and Conway, 2011).

Climate policy has focused on climate change mitigation through the reduction of GHG emissions. Similarly, there is a need to adapt to climate variability (Bhullar, 2013). Climate change is a global occurrence with regional economic, political, and physical impacts and implications. Adaptation to climate change depends on regional and local geographic and economic diversity to assess the effect at a specific level (Bhullar, 2013).

Assessment tools that measure the ecological status, environmental degradation, and depletion of natural resources are essential for long-term natural resources' management (Al-Kalbani et al., 2016). Different approaches have been adopted to evaluate engineering systems, each of them has got its advantages and unique features. Quantitative and qualitative methods are applied to evaluate technical, economic, environmental, and social performance of water and sanitation supply chain options that include mathematical optimization, multi-criteria decision analysis, specific net present value, and statistical analysis (Balfaqih et al., 2017), these methods have not quantified the influence of energy on water systems, yet.

Some life cycle assessments (LCA) (Fang et al., 2016; Gibon et al., 2015; Santoyo-Castelazo and Azapagic, 2014; Svanström et al., 2014) propose handling the measurement from different points of view. Santoyo-Castelazo and Azapagic (2014) frameworks include scenario analysis, LCA, life cycle costing, social sustainability assessment, and multicriteria decision analysis to assess and identify the most sustainable energy option, as well as develop a decision-support framework for a sustainable integrated evaluation of energy systems considering environmental, economic, and social aspects. Svanström and coworkers (2014) introduced an iterative assessment approach with a life cycle perspective that considers technical, economic, and environmental aspects, which refine and converge different performance aspects, especially when dealing with large complex systems. The modeling framework proposed by Gibon et al. (2015) is an integrated hybrid LCA with a focus on the environmental and economic model with integrated scenarios of climate change mitigation measures used to evaluate various technologies. Fang and coworkers LCA (2016) was used in the early research and development phase of a new wastewater process to identify the environmental trade-off of current technologies as a decision-support tool.

Some approaches select information before making an assessment, adding an extra step to the analysis to minimize the amount of data. Statistical approach based on K-means clustering was applied to manage environmental energy data to evaluate energy from renewable sources (Di Piazza et al., 2011). The assessment framework proposed by Cominola et al. (2015) automatically selects the most valuable information using a quantitative metric to operationally and economically assess water system performance.

Other frameworks propose optimization solution for scheduling environmental water flow management alternatives under changing environmental availability conditions. These frameworks are a multi-objective optimization approach for long-term planning, where forecasting is sustained by artificial neural network (ANN) models and schedules updated on an annual basis (Szemis et al., 2014). Mathematical and conceptual models used by Haasnoot et al. (2011) describe natural environment and a socioeconomic system but uncertainty limits their capacity to understand and predict future conditions.

Individual tools have several limitations when it comes to boundary conditions, spatial specifications, interventions, and types of impact (Chen et al., 2012). However, integrated tools add on complexities and problems to the modeling or analyzing all accumulative and interactive environmental effects (Chen et al., 2012) and call for a substantial amount of effort to meet methodological requirements (Svanström et al., 2014). The frameworks require extensive data and information to be examined, and some authors suggest increasing the number of variables to enhance the effectiveness of their framework (Cominola et al., 2015). Besides, a higher number of indicators does not necessarily lead to a better average result, due to difficulties in weighing the indicators and deciding about their relative importance (Strezov et al., 2017). Access to data is crucial for determining the definition of system boundaries, sometimes disregarding variables when data outside of the public domain have a significant impact on the result.

The increased stress on natural resources highlights the need to improve our understanding of these resources through the use of data to ensure equitable and safe access to natural resources for humans and the environment (Chini and Stillwell, 2018). The inclusion of water-energy nexus principles into modeling frameworks enables more understanding and better decision-making (Chini and Stillwell, 2018). The complexity can be reduced by dividing the analysis of the water-energy nexus into two components: energy-for-water and water-for-energy (Chini and Stillwell, 2018). By choosing to work with only one component, energy-for-water, we can manage more variables and better analyze the system in question and its interactions. This framework is applied to the energy-for-water component with the aim to manage fewer data, and to ease the generation of alternatives from which decision-makers can endorse they rule.

Based on a simplified decision-support framework, we can environmentally assess seawater treatment and distribution system for different water quality requirements, topography scenarios, and energy mixes. Our goal was to estimate GHG emissions and their environmental consequences for every location to compare the same scenario for every country. Evaluations are performed using literature data, such as those from the techno-economic assessment completed by Tavakkoli and coworkers (2017), with the purpose of calculating the impact of the system while demonstrating the unbreakable bond between water treatment and energy demand.

2. Materials and methods

Water treatment process and distribution are involved in a complex and dynamic system including climate, biological, hydrological, physical, and human interactions (Blanc et al., 2014), meaning water management must overcome significant challenges, including stricter water quality standards, increased water demand, and adaptation to climate change. Simultaneously, GHG emissions must be reduced, and a sustainable management framework must be provided for water resource treatment and transportation (Rothausen and Conway, 2011).

Water supply and demand depend on factors such as population growth, increasing urbanization, intergovernmental relations, political and policy choices, social factors, technological growth, and climate uncertainties (Plappally and Lienhard, 2012). By assessing water treatment processes, performance measures and metrics allow for the continuous improvement of water supply chain and can be used to report the current situation, with a better understanding of the past, while helping to identify future goals (Balfaqih et al., 2017).

The decision-support framework is based on the definition of

the preliminary design of a treatment unit (Svanström et al., 2014). It stipulates that the initial plan of a treatment unit includes the development of a flow sheet for mass balance calculation, quantitative characterization of water and sludge streams, and data collection (Svanström et al., 2014). The framework can be applied as a strategy when environmental and ecological impacts are not to any market price mechanism. So, to be quantified, the non-market value of natural resources can be assessed for decision-making purposes (Chang et al., 2012). Sometimes it is not possible to show returns from environmental investments in the short term; however, if required by the regulations, an investment may be necessary for operational continuity or to avoid negative consequences (Salomaa and Watkins, 2011).

2.1. Scenario definition

To define a system we need to delimitate borders, develop a scenario, collect data, and assess its performance. System boundaries delimitation is essential, especially when considering assessments outside of the water industry. Water treatment chain can be divided into several stages: water supply, water treatment, residential end-use, wastewater treatment, and agriculture end-use. The basic hydrologic cycle of water engineering systems can be separated into potable water production, distribution, and consumption, and wastewater collection, treatment, disposal, and reuse (Xu et al., 2001). Each stage can be affected by geographic location, water availability, local climate, culture and customs, and economic status (Plappally and Lienhard, 2012).

The scenario used for this assessment is presented in the flowsheet in Fig. 1. All the systems are analyzed under different energy arrangements, presented for countries with water scarcity problems. As a comparison, we use GHG emissions in grams of carbon dioxide equivalent. Fig. 1a provides a graphic overview of System A boundaries intended for municipal water use, following wastewater treatment and disposal. Treatment A involves several alternatives of seawater desalination through multi-effect distillation (MED), multistage distillation (MSF), reverse osmosis (RO), brackish RO, and electrodialysis, along with their energy consumption. For all the treatment processes analyzed for System A (Fig. 1a) we assumed the same chemical consumption and the same wastewater rejection per cubic meter of seawater treated.

Fig. 1b provides a graphic overview of System B boundaries, intended for municipal use, with the same treatment process alternatives as in System A: MED, MSF, RO, Brackish RO, and electrodialysis, but with the addition of posterior wastewater recycle, where water is planned to be used for irrigation purposes. For all the treatment processes in System B (Fig. 1b), we also considered the same chemical consumption and the same wastewater rejection per cubic meter of seawater treated. Finally, Fig. 1 c provides a graphic overview of System C boundaries, where seawater is non-desalinated, without treatment (WT), intended for the industrial purpose. After it is used, water recirculates through industrial processes.

There are two types of common, obvious errors: systematic errors or biases that decrease the accuracy of the estimates and random errors that reduce the precision of the forecast. The lack of accuracy and precision may lead to uncertain estimates, but we can deal with precision errors by increasing the number of samples, whereas bias can be reduced by monitoring and reporting (Bellassen and Stephan, 2015). However, when analyzing complex systems, we need to reduce the number of samples to ensure that calculation is manageable. In this study to decrease the bias, calculations were completed under best, worst, and average case scenarios, with data supplied by peer review articles, the World Bank (The World Bank, 2017) and Organization for Economic Cooperation and Development (OECD) data ("Waste water treatment - Water - OECD iLibrary," 2017).

To represent best, worst, and average case scenarios, we considered different distances (horizontal and vertical) from which seawater must be pumped to be treated and distributed, as shown in Fig. 2. The best-case scenario considers the shortest distance, vertically and horizontally, from seawater extraction site to the treatment plant and towards end-user location. The worst-case scenario involves the longest distance from the extraction zone to the treatment plant, and afterward to the end-use zone. The average-case scenario represents the in-between situation of the other two cases. Cases considering vertical and horizontal distance represent different topographies in the analyzed countries and different water distribution paths from extraction to end-user location. Also, we assessed different types of water demand with three water treatment flows: low, medium, and high. Data used to define all scenarios were taken from literature as shown in Table 1.

2.2. Case study

The framework was applied to a selected number of countries experiencing water scarcity as listed by Mekonnen and Hoekstra (2016) or countries located in regions with water problems and with access to the coastline. The group of selected countries included: Argentina, Australia, Algeria, Bahrain, Bangladesh, Chile, China, Arab Republic of Egypt, India, Indonesia, Israel, Iran, Iraq, Italy, Kingdom of Jordan, Kuwait, Lebanon, Libya, Malaysia, Mexico, Morocco, Nigeria, Oman, Pakistan, Portugal, Saudi Arabia, South Africa, Sudan, Syrian Arab Republic, Spain, Tunisia, Republic of Turkey, United Arab Emirates, United States of America, and Yemen. We also used average world GHG emissions. Data included Finland to show that not only renewable energy but also nuclear energy generation, as used by Spain, can decrease GHG emissions. The results for all these countries are provided in the Supplementary Information section.

3. Data collection and water characteristics

Data collected for the systems covered by our study are summarized in Table 1. Variables considered for each modeling situation are shown in bold in Table 1. The data were obtained from peer review articles (Cong et al., 2009; Jamaly et al., 2014; Kesieme et al., 2013; Macedonio and Drioli, 2017; Petry et al., 2007; Plappally and Lienhard, 2012; Racoviceanu et al., 2007; Stokes and Horvath, 2009; Tavakkoli et al., 2017). For calculation, we chose the best, worst, and average scenario for every low, medium, and high water treatment flow.

For quantitative characterization, water and sludge were assumed the same for all cases in our study to facilitate the comparison of results.

3.1. Balance calculation

3.1.1. Mass balance

Environmental impacts of a flow can be calculated using a simple mass balance of all associated inputs, outputs, and storage (Chen et al., 2012). For each system, we calculated the mass balance of water flow based on the cubic meters of seawater treated with data from Table 1, using the feed seawater in bold for each type of treatment, obtaining the results in cubic meter per day.

3.1.2. Energy consumption balance

The energy balance was based on the mass balance with data from Table 1. The feed seawater data were used for calculations across the system, with three types of water demand: low, high,

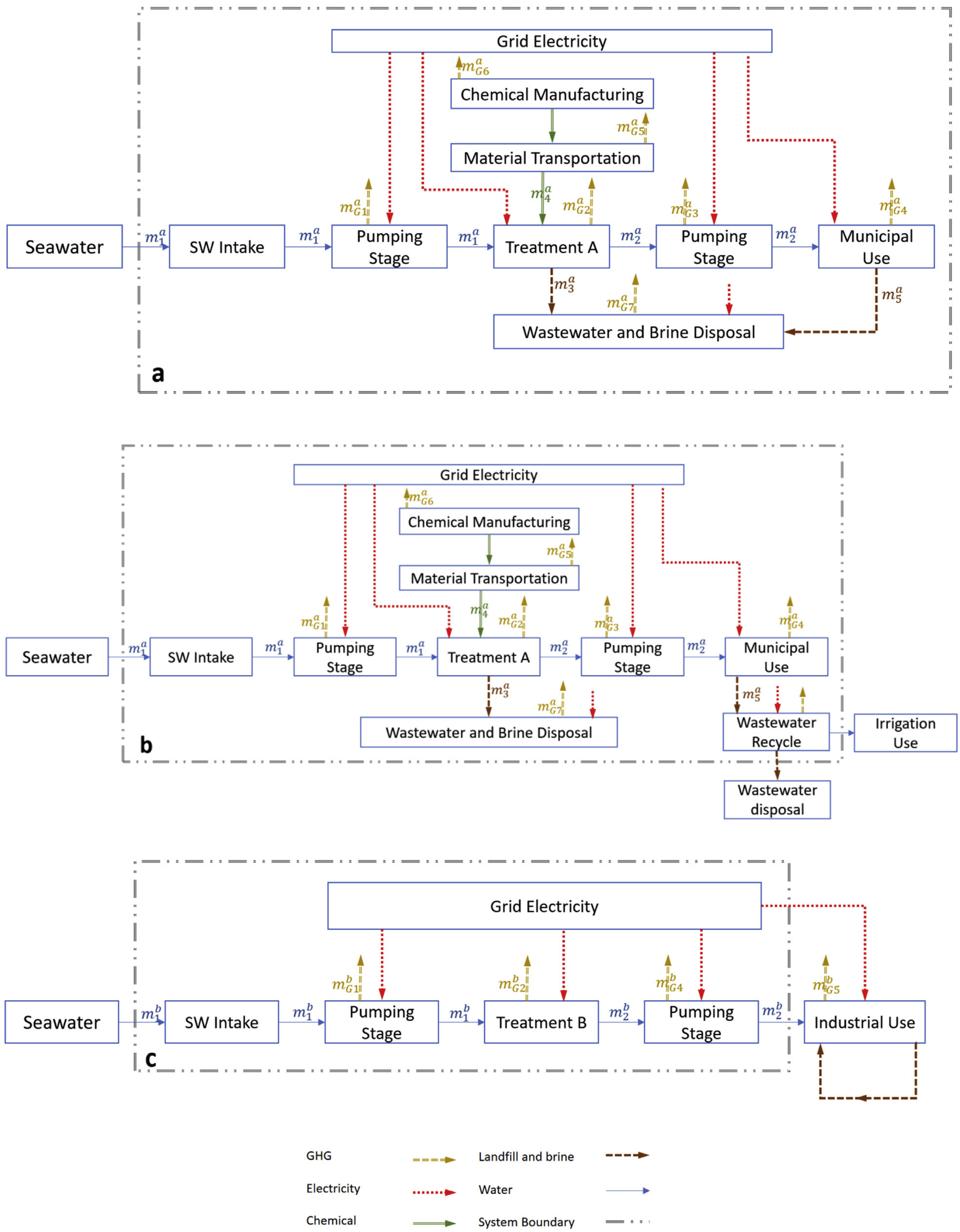

Fig. 1. Graphic overview of the boundaries of a. System A intended for municipal water use, b. System B with wastewater recycling, c. System C proposed for the industrial purpose.

and medium. Calculations were completed for each type of treatment, and results obtained are presented in kilowatt-hour per day.

- Seawater intake stage: horizontal distance data and energy consumption were calculated for the three scenarios: best, worst, and average.

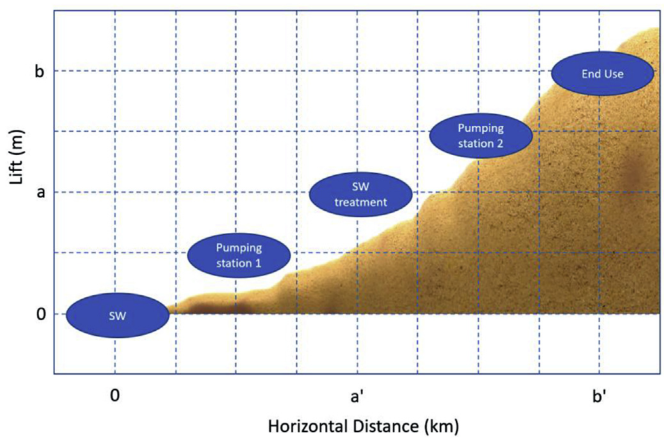

Fig. 2. Vertical and horizontal distance for seawater (SW) treatment and distribution throughout the use and treatment journey.

- Pumping station 1 stage: the data used were applied to a primary theoretical physical relationship presented (Rothausen and Conway, 2011):

$$\textit{Energy Consumption}\ [\mathrm{kWh}] = \frac{9.8\left[\frac{\mathrm{m}}{\mathrm{s}^{-2}}\right] \times \mathrm{d}[\mathrm{m}] \times \rho\left[\frac{\mathrm{kg}}{\mathrm{m}^3}\right] \times \mathrm{Q}\left[\frac{\mathrm{m}^3}{\mathrm{day}}\right]}{3.6 \times 10^6 \times \eta[\%]}$$

where d is the vertical distance, ρ is the density of seawater 1025 (kg/m^3), Q is the volumetric flow of seawater, and η is the efficiency. The variables considered for each scenario were distance and efficiency, calculated for the three types of water demand.

- Seawater treatment stage: each type of treatment with its energy consumption was calculated. Also, in this stage, we added the energy consumption of chemical manufacturing and transportation based on the amount of seawater treated. This stage was omitted for System C.
- Pumping station 2 stage: this is the second half of calculations for Systems A and B based on the quantity and quality of treated water. However, calculations remain the same for System C. Horizontal energy consumption was calculated for three scenarios with variables in distance and energy consumption. The latter was supplemented with energy consumed for vertical transportation, calculated in relationship to water density of 1000 (kg/m^3) and the same variables.
- Municipal use (end-use) stage: energy consumption was calculated based on average work (Plappally and Lienhard, 2012), due to its high variability. This stage was not calculated for System C.
- Wastewater treatment stage: this stage was calculated for System A, assuming no losses to the system.
- Wastewater recycling stage: this stage was calculated for System B, assuming no losses to the system, and the product water is intended for irrigation.
- The last step consists of adding up all energy consumed in each system and then calculating the GHG emission per country based on the type and amount of generated energy. To evaluate GHG emissions, we used data from Table 2, where A corresponds to the data from Amponsah et al. (2014) and B corresponds to Racoviceanu et al. (2007).

4. Results

The framework was applied to the world average as a case study, though calculations and results for all selected countries are presented in the Supporting Information section. The results are shown to illustrate the methodology and provide an understanding of the results obtained. Fig. 3 depicts the countries covered by the analysis of average GHG emissions, and in Fig. 4 we compare these emissions with the world average.

Fig. 5 demonstrates the mix of energy sources used for each

Table 1
Input values obtained from literature that were applied in the framework.

	Values used in the application of the framework are shown in bold and subscript numbers: $_1$best case, $_2$average case, and $_3$worst case.								
Seawater Intake	Feed Seawater (m^3/day)	**1,893**[a]$_1$	24,000[b]	37,450[b]	45,360[c]	**90,000**[d]$_2$	**432,000**[e]$_3$		
	Horizontal distance (km)	**1**[f]$_1$	3.2[f]	4.8[f]	125[f]	170[c]	**236**[g]$_2$	400[f]	**1,100**[f]$_3$
	Energy Consumption (kWh/m^3 km)	0.002[h]$_1$	0.005[h]$_2$	0.007[h]$_3$					
Pumping Station 1	Vertical Distance (m)	10$_1$	648[g]$_2$	3,200[c]$_3$					
	Efficiency (%)	**40$_3$**	50	60	**70$_2$**	80	**90$_1$**		
Seawater Treatment	Treatment Type	MED	MSF	RO	Brackish RO	Electro-Dialysis	Without treatment		
	Recovery (%)	50[e]	50[e]	50[e]	50[e]	50[e]	100		
	Energy Consumption (kWh/m^3)	1.79[h]	3.84[h]	5.02[h]	1.63[h]	1.25[h]	0		
Chemical Manufacturing	Energy Consumption (kWh/m^3)	0.039[i]							
Chemical Transportation	Energy Consumption (kWh/m^3)	0.008[i]							
Pumping Station 2	Water treated (m^3/day)	**946.5$_1$**	12,000	18,725	22,680	**45,000$_2$**	**216,000$_3$**		
	Horizontal distance (km)	**1**[f]$_1$	3.2[f]	4.8[f]	125[f]	170[c]	**236**[g]$_2$	400[f]	**1,100**[f]$_3$
	Energy Consumption (kWh/m^3)	0.002[h]$_1$	0.005[h]$_2$	0.007[h]$_3$					
	Vertical Distance (m)	10$_1$	648[g]$_2$	3,200[c]$_3$					
	Efficiency (%)	**40$_3$**	50	60	**70$_2$**	80	**90$_1$**		
End-Use	Energy Consumption (kWh/m^3)	66.57*[h]							
Wastewater Treatment	Energy Consumption (kWh/m^3)	0.20[i]$_1$	0.30[i]$_2$	0.42[i]$_3$					
Wastewater Recycling	Energy Consumption (kWh/m^3)	0.33[i]$_1$	0.91[i]$_2$	1.86[i]$_3$					

[a] Tavakkoli et al. (2017).
[b] Kesieme et al. (2013).
[c] Petry et al. (2007).
[d] Jamaly et al. (2014).
[e] Macedonio and Drioli (2017).
[f] Stokes and Horvath (2009).
[g] Cong et al. (2009).
[h] Plappally and Lienhard (2012).
[i] Racoviceanu et al. (2007); and.
*calculated based on data from Plappally and Lienhard (2012).

Table 2
GHG emission data for energy generation in gCO_2eq/kWh. Information from A corresponds to the data from Amponsah and coworkers (2014) and B corresponds to Racoviceanu and coworkers (2007).

Renewables		Hydro	38.5^A
Wind	64.5^A	Coal	1031^B
Geothermal	44.5^A	Oil	792^B
Photovoltaic	154.5^A	Natural Gas	397^B
Solar Thermal	90^A	Nuclear	14^B
Prom Renewable	88.4	Biofuels and Waste	332^A

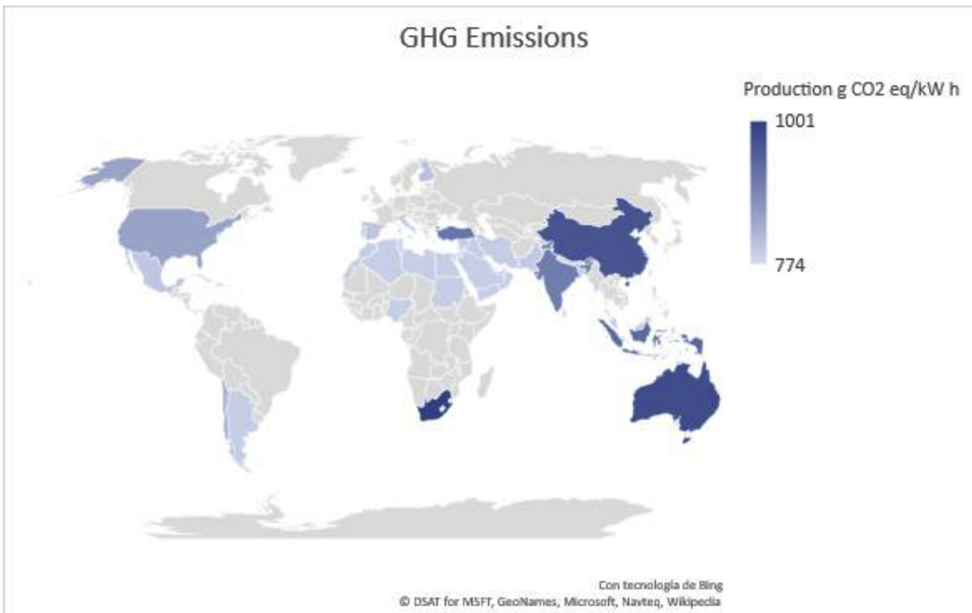

Fig. 3. Map of GHG emissions in analyzed countries based on the production of gCO_2 equivalent per kWh; data calculated based on IEA – Report (IEA, 2011).

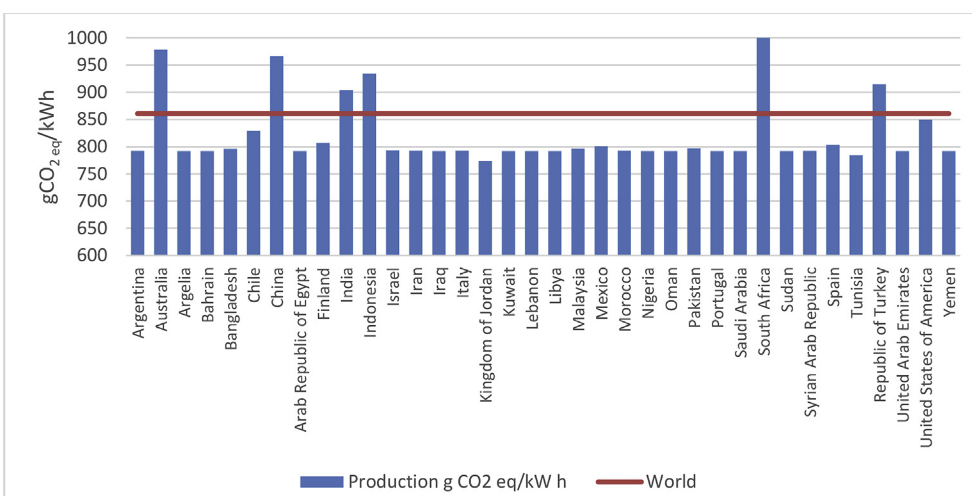

Fig. 4. GHG emission comparison with the world average based on the data from IEA – Report (IEA, 2011).

selected country, which includes: coal, crude oil, natural gas, nuclear, hydro, renewable sources (geothermal, solar, wind, and others), biofuel, and waste (OECD, 2018). Fig. 5 presents GHG emissions in ascending order, from the lowest releasing country in the analyzed sample, Kingdom of Jordan, to the biggest emitter, South Africa.

Fig. 6 displays energy consumption in different seawater desalination processes analyzed in this work. Table 3 shows calculations for the three analyzed scenarios: low consumption (1893 m^3/day), medium consumption (90,000 m^3/day), and high consumption (432,000 m^3/day) of treated water.

Fig. 7 is a graphic representation of GHG emissions for three

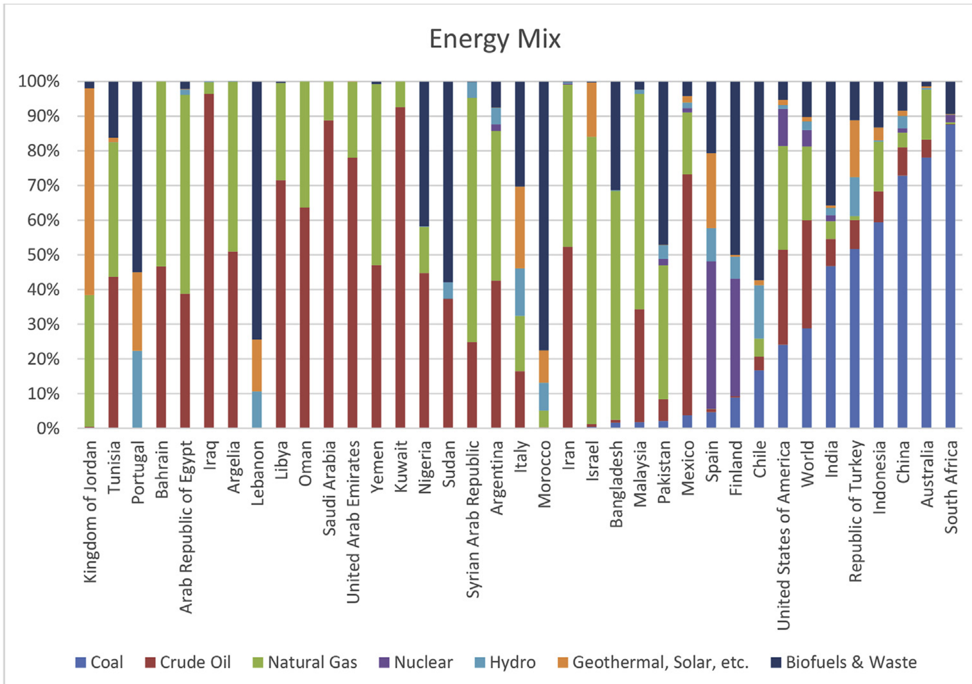

Fig. 5. Diversity of energy mix generation based on previously reported data (IEA, 2011).

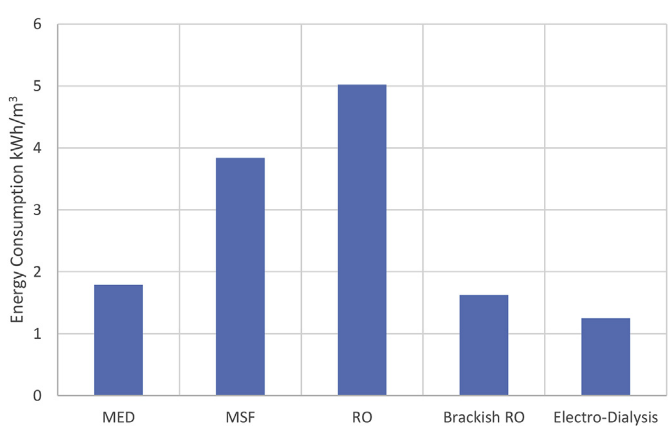

Fig. 6. Energy consumption for different types of seawater desalination treatment complete the analysis, we left some variables unchanged to show more relevant results.

types of water demand. We selected countries with the highest and lowest release from our study sample and compared them with the world average emissions. Fig. 7 displays the results corresponding to the world average, South Africa, and The Kingdom of Jordan GHG emissions. First, the GHG emissions from the treatment of wastewater from residential end-users and its disposal (System A, correspond to the first five technologies on the graph). Second, the GHG emissions from wastewater recycling from residential end-users to irrigation applications (System B, correspond to the second five technologies on the graph). Finally, the GHG emissions from untreated seawater intended for industrial use (System C, corresponding to the last group of columns). The results consider energy consumed by pumping seawater at different distances and heights.

5. Discussion

Systems engineering strategy frameworks are sufficiently flexible to support a broad range of applications and contribute to an organization's sustained competitive advantage (Smartt and Ferreira, 2012). The challenge is that engineers and technical managers must consider the technological system as part of a larger whole (Svanström et al., 2014). However, larger technological systems have countless opportunities for isolating subsystems to enable comprehension and analysis (Bartolomei et al., 2012). Inability to carefully understand the subsystem can lead to only

Table 3
Energy consumption for analyzed seawater treatment processes.

Energy Consumption for Treatment (kWh/day)			Seawater Consumption (m^3/day)		
Type of Treatment	Recovery (%)	Energy Consumption (kWh/m^3)	1893	90,000	432,000
MED	50	1.79	3388	161,100	773,280
MSF	50	3.84	7269	345,600	1,658,880
RO	50	5.02	9503	451,800	2,168,640
Brackish RO	50	1.63	3076	146,250	702,000
Electro-Dialysis	50	1.25	2366	112,500	540,000
Without treatment	100	0.00	0	0	0
	Water out (m^3/day)	50%	947	45,000	216,000
		100%	1893	90,000	432,000

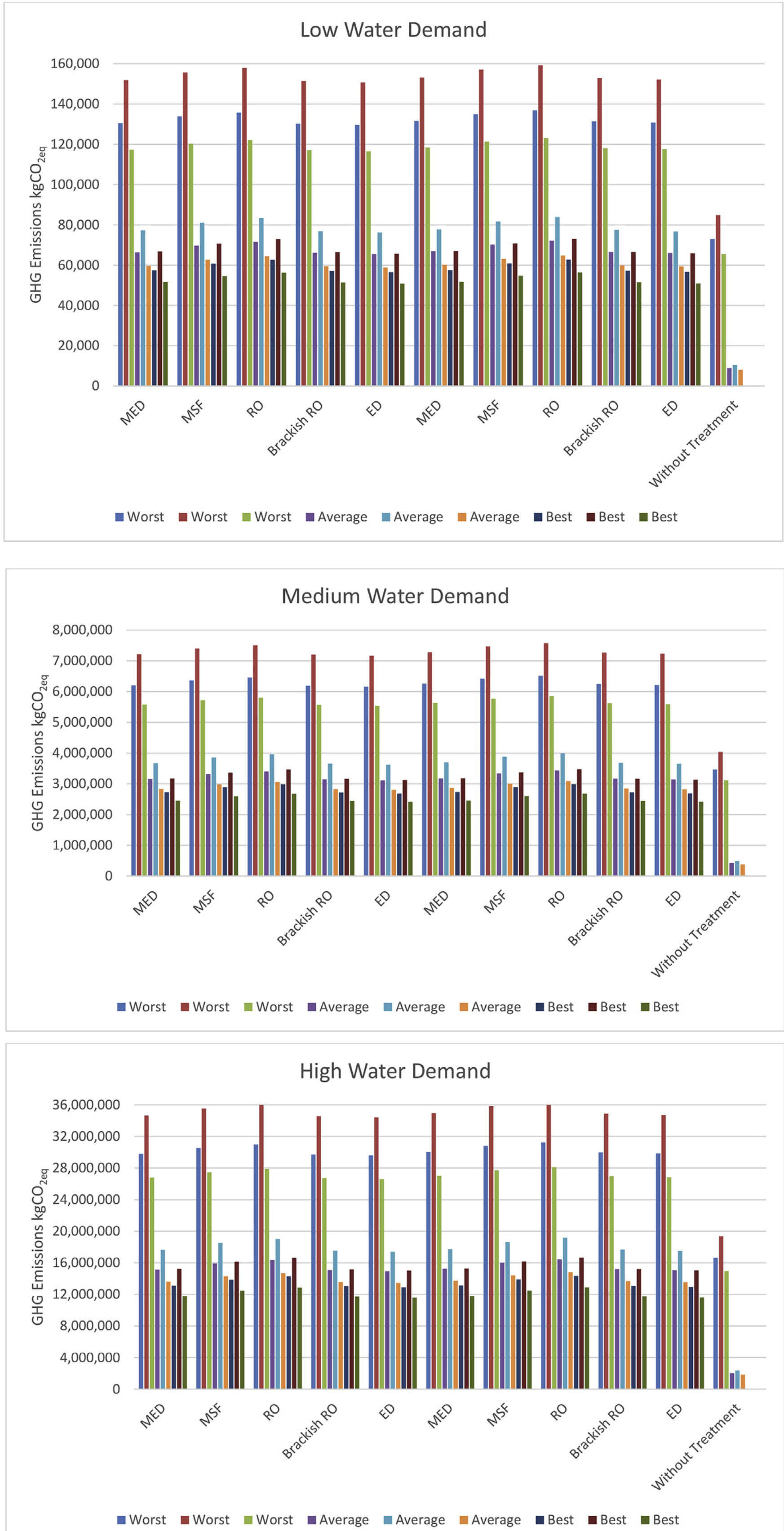

Fig. 7. Comparison of GHG emissions between countries with the highest, lowest and world average releases for different water demand. More details about the calculations and results can be found in the Supplementary Material.

partial, or even distorted, picture of the system behavior, which argues in favor of our decision to consider only the energy-for-water component of the water-energy nexus in this analysis. We chose to study the energy-for-water component to facilitate the aim of generating a framework that is simple and fast in providing results for the endorsement of the decision-making process.

Analyzing individual sectors without considering their interaction with each other can lead to misinterpretation of impacts and therefore to poor decisions (Harrison et al., 2016). Water and energy are inseparably associated because water is a crucial component in energy production and vice versa. Energy is needed for supplying, treating, and using water. In all cases analyzed by Loubet and coworkers (2014), electricity contributed to the majority of impacts in water treatment, and particularly in desalination processes, where energy requirements are higher than in conventional water treatment processes. However, analyzing the components of the water-energy nexus is a challenging endeavor. For this reason, we only examined the energy-for-water component to facilitate obtaining results more quickly.

Energy consumption also depends on the specific technology applied at each stage of the water cycle and on the water source (Plappally and Lienhard, 2012). Water treatment technologies have been introduced to improve water quality, with technological developments that provide options for design or advances in previous water treatment processes (Ramírez et al., 2017). The type of technology selected depends on other variables, such as the analysis of technologies influencing the energy-for-water GHG emissions as was compared as Treatment A types in systems A and B (see Fig. 1). However, the selection of water treatment technology should consider GHG emissions. RO is the most frequently used water treatment technology, but it produces the biggest GHG emissions (see Fig. 6), which gives us three options: to select a technology with lower GHG emissions, to improve the current technology to consume less energy, or to opt for a lower GHG emission source of energy.

When analyzing the energy mix for providing electricity in Figs. 4 and 5, the alternatives for reducing GHG emissions include opting for renewable sources of energy and/or nuclear energy. This is shown in the results obtained in the analysis of the energy mix for countries like Spain and Finland and supported by the results obtained by Santoyo-Castelazo and Azapagic (2014), where energy sources, such as nuclear power release less GHG emissions than renewable energy (see Table 2). Countries with lower GHG emissions do not use coal as energy source (see Fig. 5, from the Kingdom of Jordan to Israel). Moreover, countries with the highest GHG emissions are those with coal as a principal source of energy (see Fig. 5, from India to South Africa), nearly 50% and over. However, public approval is vital for the implementation and operation of any water treatment system. Factors influencing public acceptance are disgust, perception of risk, sources of water for recycling, specifically for the intended use of recycled water, trust in authorities, knowledge, attitudes toward the environment, environmental justice, cost, and socio-demographic factors.

The analysis of different scenarios of seawater desalination processes for several countries facing water scarcity problems showed that a diverse energy mix has got an essential impact on GHG emissions. The location of the water source and end-users produce the most prominent environmental effects if we only consider energy-related emissions. These metrics provide opportunities to develop and understand the impact of topology on energy consumption to deliver water for industrial, irrigation, and municipal purposes. Seawater treatment and distribution system efficiency must be improved (Cisternas and Gálvez, 2018). Mining operations that are located at high altitudes entail increased costs of using seawater, either with, without, or with partial desalination, due to transport costs. The supply chain in the analyzed scenarios differs with respect to the selected technology, which influences economic and environmental performance. Therefore, a generic supply chain is not sufficient in the framework for informed decision-making (Ribeiro et al., 2016).

Countries located in non-arid regions can experience water supply deficiencies. Singapore's strategy involves local catchment water and desalinated water in addition to water imported from Malaysia (Bhullar, 2013). Desalination expands domestic water supply sources, as the geographic location does not require much energy, due to the highest point being located 165 m above sea level, and the entire population lives less than 100 km from the coast (Bhullar, 2013).

Stakeholders must be provided with all alternatives to select and implement the best-case scenario for the market, especially when, as is the case here, all the countries included in this study present a variety of geographic challenges and a diversity of user locations. Water utilities should assess their management strategy to ensure a high level of service, safe and reliable drinking water, and appropriate network performance, which requires a suitable long-term balance between cost, performance, and risk at the strategic and operational levels (Feliciano et al., 2014). Public perception and acceptance are critical to the implementation of any energy technology (Santoyo-Castelazo and Azapagic, 2014). Government policies and stakeholders' approval depend on the location as well as on specific political, social, and economic circumstances (Svanström et al., 2014) that vary across all the analyzed countries. An integrated management strategy should be adopted to allow sustainable development of the industry for all stakeholders (Oyarzún and Oyarzún, 2011).

Water desalination sustainability involves improved human health, environment, and fresh water for domestic, industrial, and agricultural use (Balfaqih et al., 2017). Other alternatives, such as complete reuse of wastewater, can be competitive options in the market due to the increasing demands on environmental policy, changes in public attitude, and water technologies advancement (Xu et al., 2001). Also, the selection of these alternatives can lead to non-conventional water sources becoming an alternative for other areas that are not facing severe water scarcity problems. Desalinated water could be an economically competitive option, producing a less negative impact on the environment. Water desalination, however, is a management and technical solution that is not self-sufficient; the price and availability of energy determine the future price and availability of water. Desalination is costly, energy-intensive and leaves a huge ecological footprint (Bhullar, 2013).

In Northern Chile, conventional water sources are scarce, affecting water reservoirs that provide flow for water springs and Andean wetland ecosystems. These ecosystems are essential for the pastoral activities of Aymara native communities and natural habitats of the local population of flamingos and other wild species (Oyarzún and Oyarzún, 2011). Sustainable water management is complicated and the concern over water scarcity is growing (Loubet et al., 2014). Sustainable water management should include conservation, recycling, and desalination (Mezher et al., 2011). Urban water systems are elaborate and embrace many aspects that often require separate management. Integrated urban water management is a general approach that requires quantitative tools to assess environmental impacts and involves water sources, water use sectors, water services, and water management scales (Loubet et al., 2014). The end-use water consumption can vary significantly from one person to another, as shown by Plappally and Lienhard (2012), therefore end users' unpredictable behavior is a non-reliable tendency. The environmental regulatory system quality and stringency are related to national wealth (Salomaa and Watkins, 2011). To

develop a sustainable water management strategy involves the identification of vulnerable and adaptation possibilities, and compelling analysis under possible futures must be completed (Haasnoot et al., 2011).

Limitations of this decision-making framework for the environmental assessment of water treatment processes and distribution systems come from its concept of a simplified framework, which makes assessments of more complex systems that involve, e.g., different types of energy sources in different parts of the system, a really daunting task in practice. Also, a great challenge will be to consider the water-for-energy component of Water-Energy nexus, redefine the analyzed system or insert more variables and interactions into the mix.

6. Conclusions

A decision-support framework was proposed and developed in this study to analyze the energy-for-water component of the water-energy nexus. This framework was applied to water treatment and water distribution systems and their impact on the environment. This work aimed to show the lasting relationship between water and energy, analyzing the energy-for-water component against GHG emissions and its variability throughout water systems.

It is essential to assess the energy mix diversity given the effects of water treatment and consumption on the environment so that stakeholders could make better decisions, and improve the overall consumer awareness. Water and energy are inseparably associated given the energy required for the processes of supplying, treating, and using water. Electricity is responsible for the most significant part of the impacts of water treatment, particularly in desalination processes, where energy requirements are higher than in conventional water treatment processes. The location of water source and of the final consumer cannot be changed, however, improvements in the selection of technology, energy source, and the promotion of water reuse, water recycling, and non-treated water for industrial processes can be improved to help lower GHG emissions from water treatment processes and water distribution systems.

The different water process systems analyzed for several countries facing water scarcity problems showed that a diverse energy mix is the main factor affecting GHG emissions. The locations of the water source and end-users have the most significant impact on the environment if solely energy-related GHG emissions are considered. To lower GHG emissions, one of the options is to opt for a different source of energy having in mind that nuclear power generation produces the lowest GHG emissions, even lower than renewable energies. However, to develop new projects or to improve the existing ones it is vital to consider stakeholders' opinions, to start or continue such operations.

Water sustainability alternatives can also be applied to zones not experiencing severe water scarcity. Water desalination, water reuse, and wastewater treatment can be competitive options for the market due to the increasing demands of environmental policy, changes in public attitude, and advancements in water technologies. Public perception and approval are critical for the implementation of any water treatment project, especially when water is intended for drinking purposes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2019.03.319.

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